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Interoperable Open-Source Sensor-Net Frameworks With Sensor-Package Workbench Capabilities:

Motivation, Survey of Resources, and Exploratory Results

Jayson Durham
SPAWAR Systems Center – Pacific (SSC Pacific)
Advanced IO Capabilities Branch, San Diego, CA USA
Email: Jayson.Durham@navy.mil

Mehrube Mehrubeoglu
Texas A&M University–Corpus Christi,
Department of Computing Sciences, Mechanical Engineering, and Engineering Technology
Corpus Christi, TX USA
Email: Ruby.Mehrubeoglu@tamucc.edu

Lifford McLauchlan
Texas A&M University-Kingsville
Electrical Engineering and Computer Science Department
Kingsville, TX USA
Email: Lifford.McLauchlan@tamuk.edu

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14. ABSTRACT
Low-cost sensor technologies, such as Micro-Aerial Vehicles (MAVs), present an opportunity to facilitate improved transformational Intelligence, Surveillance, Reconnaissance Targeting, and Information Operations (ISRT/IO) capabilities in support of tactical network-centric ISRT/IO Warfighter and First-Responder operations. There is an exigency for realistic rehearsal frameworks to enable efficient and rapid deployment of MAVs in support of ISRT/IO; physics-based 3D simulation and modeling capabilities improve mission planning and efficiency. The incorporation of Free Open Source Software (FOSS) such as the Naval Postgraduate School (NPS) Autonomous Unmanned Vehicle (AUV) workbench into the Sensor-net Self-Organization and Control (SenSOC) initiative enables highly reconfigurable realistic and dynamic mission planning capabilities thereby creating more responsive Systems-of-Systems Engineering (SOSE). The current work, reported herein, focuses on the incorporation of a scalable sensor-package in the NPS AUV platform-oriented modeling, simulation, and experimentation framework which would support operational use-cases and CONOPS (i.e. concepts of operation) for tactical ISRT/IO mission-threads and associated scenarios.

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Jayson Durham
SPAWAR Systems Center – Pacific
(SSC Pacific)
Advanced IO Capabilities Branch,
San Diego, CA USA
Jayson.Durham@navy.mil

Mehrube Mehrubeoglu
Texas A&M University–
Corpus Christi,
Department of Computing Sciences,
Mechanical Engineering, and
Engineering Technology,
Corpus Christi, TX USA
Ruby.Mehrubeoglu@tamucc.edu

Lifford McLauchlan
Texas A&M University-Kingsville
Electrical Engineering and
Computer Science Department,
Kingsville, TX USA
kfllm00@tamuk.edu

Abstract—**Low-cost sensor technologies, such as Micro-Aerial Vehicles (MAVs), present an opportunity to facilitate improved transformational Intelligence, Surveillance, Reconnaissance, Targeting, and Information Operations (ISRT/IO) capabilities in support of tactical network-centric ISRT/IO Warfighter and First-Responder operations. There is an exigency for realistic rehearsal frameworks to enable efficient and rapid deployment of MAVs in support of ISRT/IO; physics-based 3D simulation and modeling capabilities improve mission planning and efficiency. The incorporation of Free Open Source Software (FOSS) such as the Naval Postgraduate School (NPS) Autonomous Unmanned Vehicle (AUV) workbench into the Sensor-net Self-Organization and Control (SenSOC) initiative enables highly reconfigurable, realistic and dynamic mission planning capabilities thereby creating more responsive Systems-of-Systems Engineering (SOSE). The current work, reported herein, focuses on the incorporation of a scalable sensor-package in the NPS AUV platform-oriented modeling, simulation, and experimentation framework which would support operational use-cases and CONOPS (i.e. concepts of operation) for tactical ISRT/IO mission-threads and associated scenarios.**

Keywords - MAV; UAV; micro-aerial vehicle; unmanned autonomous vehicle; sensor-net; image processing; mosaicking; georegistration; modeling and simulation; open source; X3D

I. Introduction

Low-cost sensor technologies, such as Micro-Aerial Vehicles (MAVs), present an opportunity to facilitate improved transformational Intelligence, Surveillance, Reconnaissance, Targeting, and Information Operations (ISRT/IO) capabilities in support of tactical network-centric ISRT/IO Warfighter and First-Responder operations. Fig. 1 highlights only a few of the broad range of MAVs readily available for tactical ISRT/IO applications [1]-[3]. Note that the upper right image in the figure illustrates remote launch and recovery of MAVs from unmanned ground vehicles. The figure also illustrates that MAVs enable man-packable sensor-net capabilities that, in principle, can provide organic ISRT/IO resources for individual stakeholders in the field.

Figure 1. Example Micro-Aerial Vehicles (MAVs) [1]-[3]

This tactical net-centric ISRT/IO effort, reported herein complements, and is working in collaboration with, robotics centers of excellence at SSC Pacific and elsewhere. Reviews and surveys of related robotics work are available [1]-[3]. A number of standardized and interoperable tactical robotics resources further motivate the development of interoperable open-source mission-driven sensor-net framework capabilities. For example, Fig. 2 is a screen-shot of the Multi-robot Operator Control Unit (MOCU) that supports video/imagery streams from multiple types of platforms (e.g. UAV/USV/UGV).

For rapid deployment and efficient utilization of such emerging technologies, especially in support of tactical network-centric ISRT/IO Warfighter and First-Responder operations, there is a critical need for highly reconfigurable and dynamic mission planning and rehearsal frameworks with highly-integrated workbench facilities.

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Figure 2. Screen-Shot of MOCU Configured as A Multi-Vehicle (UAV/USV/UGV) Controller with Video From A Manportable UGV. [2]

The survey and initial results reported in this paper are in response to a need to utilize realistic physics-based 3D simulation and modeling capabilities to enable improved mission planning and support. The inclusion of Free Open Source Software (FOSS) such as the Naval Postgraduate School (NPS) Autonomous Unmanned Vehicle (AUV) workbench described in Section III into the Sensor-net Self-Organization and Control (SenSOC) initiative facilitates highly reconfigurable, realistic and dynamic mission planning capabilities thereby creating more responsive Systems-of-Systems Engineering (SOSE). The additional incorporation of a sensor-package in the integrated FOSS would support operational use-cases (i.e. concepts of operation) for tactical ISRT/IO mission-threads and associated scenarios.

Information interoperability (i.e. sharing) is also an inherent, key operational requirement for highly coordinated rapid responses, as typically needed for effective Network Centric Warfare (NCW) and First Responder missions [4]. As Fig. 3 illustrates, improvements in information sharing directly impact dependent activities such as shared situation awareness, collaboration and self-synchronization. Thus, more interoperable and seamless planning, rehearsal, and execution capabilities are expected to dramatically improve operational mission effectiveness for tactical ISRT/IO applications.

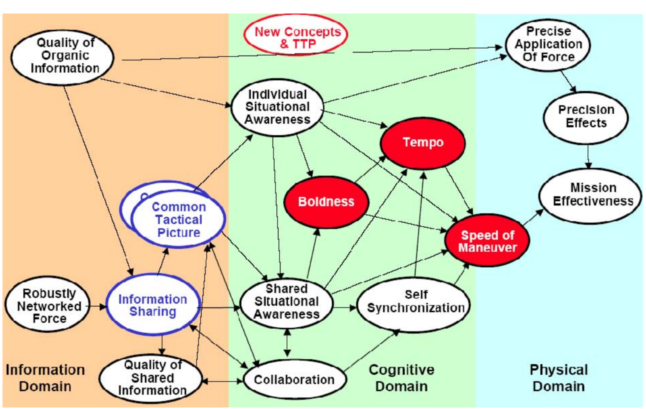

Figure 3. Tenets of Network-Centric Warfare (NCW) [4]

The SenSOC initiative focuses on developing seamless operational interoperability and self-organization capabilities that include heterogeneous ad-hoc subnets of both human and unmanned nodes within the networks of services provided by Enterprise Architecture (EA) and Service Oriented Architecture (SOA) frameworks. In other words, SenSOC concentrates on the spectrum of Research, Development, Acquisition, Test, and Evaluation/Experimentation (RDAT&E) challenges associated with sensor-net self-organization and control. Such challenges include multi-INT sensor data fusion, man-packable sensor-nets, self-synchronization, global MAV-based video reach-back, and most recently, semantically-enabled EA/SOA sensor-net capabilities [5]-[15].

Fig. 4 is a network diagram of a SenSOC-NPS experiment that demonstrated MAV global video reachback via the Internet and commercial SATCOM networking [15]. Thus, the results highlight the potential extent and range of networking capabilities that motivate the development of extensible open-source sensor-net frameworks that include seamless model driven mission planning, rehearsal, and experimentation.

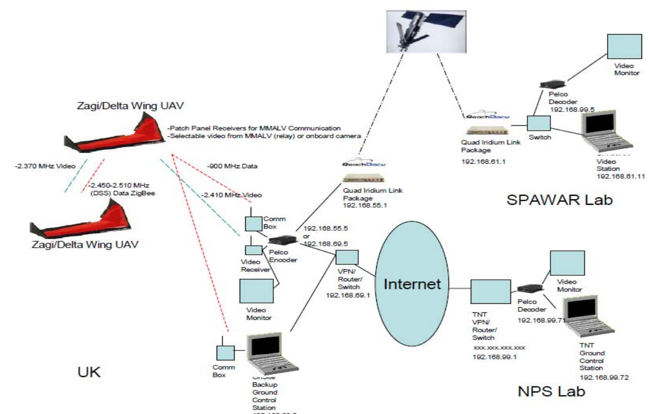

Figure 4. Network Diagram of Global Reachback Experiment [15]

In this paper, readily available open-source flight simulators and 3D modeling environments are investigated. The goal is to utilize multiple and independently developed platform frameworks to support mission needs and further enable information interoperability. A key component that is addressed includes a sensor-package workbench for facilitating the simulation of realistic mission-driven sensing capabilities, platforms/nodes, and communication networks that readily support operational use-cases (i.e. concepts of operation) for tactical ISRT/IO mission-threads and associated scenarios.

II. Needs and Emerging Capabilities

As the previous section illustrates, Warfighter and First Responder mission requirements necessitate dynamically reconfigurable sensor and communication networks that provide reliable information for improved situational awareness and rapid response. MAV technology is a high-payoff example of emerging disruptive technologies which help further enable such sensor-net capabilities. "The relatively low-cost, easy deployment, and low-detectability of MAVs provide viable next-generation NCW and first-responder solutions for mission-specific tactical ISRT/IO operations.

MAV-enabled sensor-nets provide much needed high-payoff next-generation 'eyes and ears' for Warfighters and First Responders, while keeping them out of harm's way" [56]. Also, because of their small size, MAVs are of great interest for net-centric applications, where, if needed, more than one MAV can be deployed. Multiple MAVs enable swarms and other formations of MAVs to potentially self-organize and thus, more autonomously collaborate while collecting and communicating in the operational environment. UAV research continues to be an area of much research and interest. Summaries of relevant examples of emerging inter-dependent areas of UAV research are found below.

Cooperative MAV formations need to utilize global information, efficiently manage and allocate resources (MAVs and sensors), and be robust to changing environmental conditions or mission requirements [16]. Multi-UAV relative positions can be estimated based upon each UAV's image of the scene and a derived motion field of common objects [57]-[58]. The motion fields then enable the relative displacements for each UAV to be calculated. Merino *et al.* utilize blob analysis to facilitate matching among the different UAV captured images [57]-[58]. In [17], Stolarik, Niland, and Givens studied improving the simulated MAV communications in the MultiUAV [18] multiple unmanned aerial vehicle (UAV) simulator developed by the Air Force which can simulate 8 UAVs and 10 targets. MultiUAV is a MATLAB based program. Niland discusses MultiUAV being used in the FLexible Analysis Modeling and Exercise System (FLAMES) to facilitate more complex Suppression of Enemy Air Defense (SEAD) planning [19]. MAVs which are inherently small are greatly influenced by environmental disturbances such as wind, unlike the larger Predator for example. Research into MAV dynamics and control should investigate wind effects, both on control as well as data acquisition [20]-[21]. Yao-hung and Feng estimate the error in UAV position due to the wind field and use this to correct the UAV's position [20]. Ceccarelli, Enright, Frazzoli, Rasmussen and Schumacher study target surveillance by MAVs under wind disturbances [21]. Göktoğan and Sukkarieh present a hardware in the loop (HIL) environment to further validate the simulated mission [22]. Sharma and Taylor studied multiple UAVs without GPS for navigation. Each MAV estimated its own as well as all other MAV locations and orientations. An extended Kalman filter was used to produce the position estimates [23]. Lin and Goodrich studied different algorithms for use in search and rescue path planning [24]. MAVs have also been studied for uses in environmental monitoring [25] wildlife population monitoring [26] and wildfire detection [27]. Thus, in addition to previous SenSOC related efforts, sensor-package and AUV workbench capabilities are needed to further enable environmental and wildlife monitoring and research, single and group based MAV path planning and coordination, as well as disaster management [16]-[28].

III. FOSS AUV Workbenches and Flight Simulators

A. AUV Workbench

The Modeling, Virtual Environments and Simulation (MOVES) Institute and NPS Center for AUV Research, Naval Postgraduate School, Monterey, California has created an XML based workbench called Autonomous Unmanned Vehicle (AUV) workbench [29]-[35]. This software workbench uses Autonomous Vehicle Control Language (AVCL). The AVCL includes definitions for pertinent mission data and parameters for mission simulations. AUV workbench simulations for vehicle dynamics are determined utilizing a 6 degree-of-freedom (DOF) model. The generic model can be easily changed to incorporate new vehicle dynamics or new vehicles. Background scenes during the simulation are created using Extensible 3D (X3D). Missions can also be mapped out using the 2D mission planner. Fig. 5 is a snapshot from the AUV workbench [29]-[35].

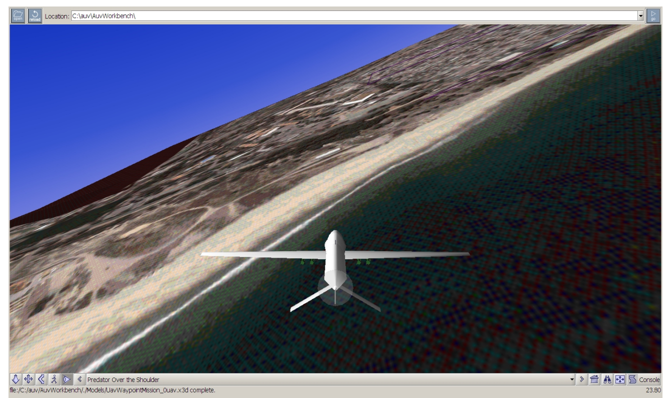

Figure 5. from MOVES AUV Workbench [29]

Fig. 6 depicts a two vehicle 3D mission planning simulation. This capability for multi-vehicle simulations is an advantage of AVCL. AVCL's ontology defines common unmanned vehicle function relationships that in turn enable multiple vehicle interactions in a simulation. This capability as well as the generic vehicle model facilitates mission planning with different vehicles [29]-[35].

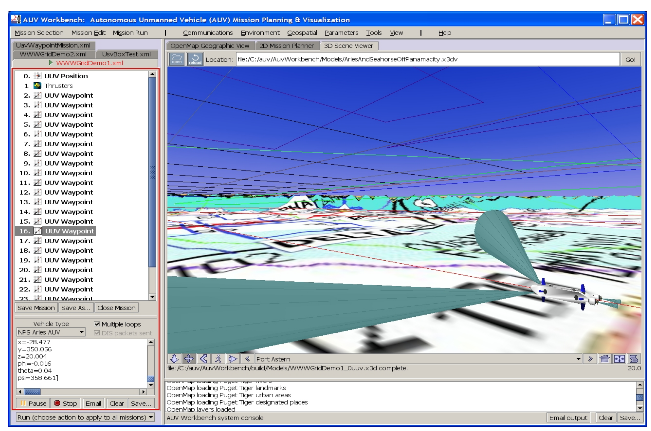

Figure 6. MOVES AUV Workbench Mission Planning Screen-Shot [29]

AVCL defines the mission using sequentially executed script commands or by defining goals which are interpreted in the form of a finite state machine (FSM). The 3D scene simulation is performed using a scene access interface (SAI) This allows the incorporation of different sensor packages. [29]-[35]. Camera models however are not included. This is a key component that needs to be addressed so that a sensor

package workbench capability incorporating camera models further enables realistic mission sensor imagery and communication data streams and their associated problems. Bandwidth limitations also play a crucial obstacle to full high resolution scene imagery being transmitted to the AUV's control station.

B. FlightGear Simulator

Another open source simulator is FlightGear [36]. The simulator runs on many of the commonly used operating systems such as Windows and Linux. An important feature of FlightGear is that it includes modifiable flight dynamics models as AUV workbench similarly includes. Other options of interest available in FlightGear include such simulator features as weather, multi-player, and GPS. FlightGear is modified easily by the user by modifying XML files, similar to modifying the AVCL files in AUV workbench. This use of XML makes FlightGear readily extensible facilitating information interoperability across various platforms.

For initial proof-of-concept and exploratory assessment, FlightGear possesses a surprising amount of interoperability due to its utilization of XML. Additionally, this exploratory assessment showcased the compatibility of the FOSS simulator across different operating systems. Due to availability and more immediate ease of use, FlightGear was utilized for synthesizing framesets used for generating simulated mosaicking results [37]-[38], [56]. A more detailed summary and discussion of FlightGear can be found in [56].

These initial results have motivated continued follow-on efforts to develop interoperable open-source sensor-net frameworks that include extensible sensor-package capabilities. This sensor-package feature complements the platform-simulation capabilities currently within the NPS MOVES AUV Workbench and other simulators. The following section describes initial progress towards developing camera modeling capabilities as an initial example sensor-package component.

IV. Camera model - Sensor Payload

As mentioned earlier, because of their small size and being relatively inexpensive, MAVs are of great interest for net-centric tactical ISRT/IO applications. Note that potentially, a significant number of MAVs can be deployed to create swarms or other large formations of MAVs that can rapidly collect and communicate data using sensor-net technology and smart cameras. Thus, multiple MAVs can cooperatively cover a large area of operation within a potentially much larger array of other fixed and mobile sensors.

Within this context, an important sensor capability is rapid collection and utilization of real time image or video scene data. Multiple scene images need to be mosaicked to produce a composite scene or aerial mosaic. Previous SenSOC experiments have demonstrated that mosaicking algorithms and software developed for larger platforms, cannot be readily applied to MAV applications. These earlier results motivate the development of camera modeling capabilities that help identify and correct such mosaicking challenges that arise due to MAV platform dynamics and typical MAV camera characteristics. Thus, initial information interoperability experimentation explores the feasibility of creating synthesized video framesets for more controlled analysis of video mosaicking results. Initial mosaicking results from synthesized framesets created using the FlightGear simulator are found in [37]-[38], [56].

Photomosaics or image mosaicking continues to attract interest in the defense as well as research communities [39]-[44]. MAVs which are inherently small are greatly influenced by environmental perturbations and disturbances such as wind. As a result, quality of MAV captured video suffers due to these disturbances; this can lead to issues in reliably and consistently mosaicking MAV captured imagery. To facilitate consistent image mosaicking, Taylor and Andersen geo-register the images used in the mosaic [39]. With this geo-registration information, the authors' method tracks virtual points between captured frames [39]. Heiner and Taylor also geo-register the mosaicked MAV captured images. However, the authors utilize information from the MAV's Inertial Measurement Unit (IMU) and the Global Positioning System (GPS) to perform this geo-registration [40] by use of a common system of coordinates. Bulo and Birk demonstrate the use of an improved Fourier-Mellin Invariant (iFMI) for mosaicking in MAV as well as underwater imagery [43]. A common method being employed for image mosaicking is the use of the Scale Invariant Feature Transform (SIFT) to determine features [41]-[42]. The SIFT determined keypoint features are scale and rotation invariant. These examples illustrate some of the various techniques and methods employed in video and image mosaicking; this demonstrates the need for a sensor-net workbench capability which will enable and facilitate an improved mission analysis and optimization.

A camera model component in the workbench will enable realistic image acquisition planning and mission modeling. The camera model will need to incorporate various parameters of interest such as operational theater and mission specific values, camera system physical and electrical characteristics, and environmental conditions. To address this need, perspective effects on the image have been examined for a generic camera model. Perspective induced effects "affect the size and direction of patterns to be recognized" [45] and so must be accounted for [45]-[46]. Fig. 7 shows the effect of camera tilt along the X-Z plane on terrain area represented by each pixel [38]. The relative distance represented by each pixel is plotted in Figs. 8 and 9 [38]. To ensure correct image mosaicking or target identification, identification of objects or processing of pixels near image edges will need to account for this nonlinear distance representation as well as possible distortion due to the camera optics. Fig. 10 shows the percent overlap between successive frames as vehicle *speed* changes on a straight path at constant altitude with the imager held parallel to terrain [38]. These preliminary camera model results highlight the added value for including a sensor-package workbench capability in the FOSS or workbench.

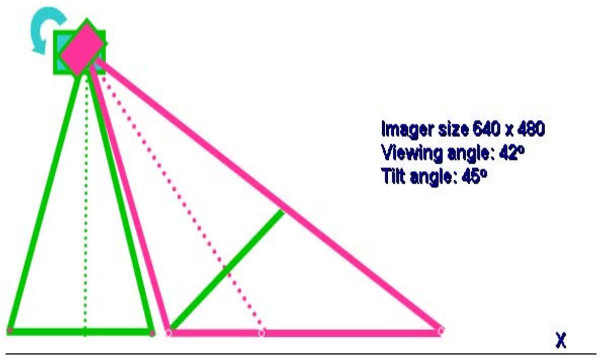

Figure 7. Effect of camera tilt along X-Z plane on terrain area represented by each pixel [38].

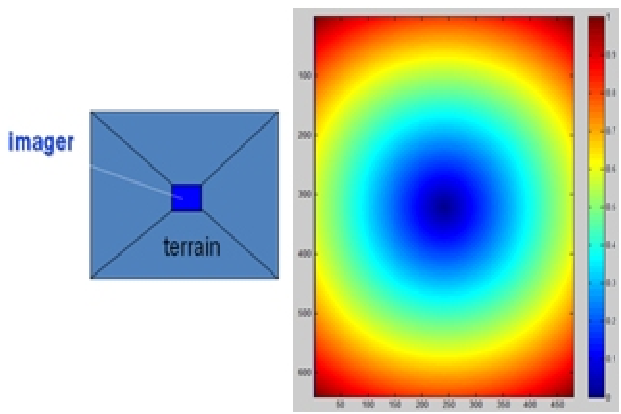

Figure 8. (Left) Camera imaging system parallel to the surface [38]. (Right) Relative distance represented by each pixel

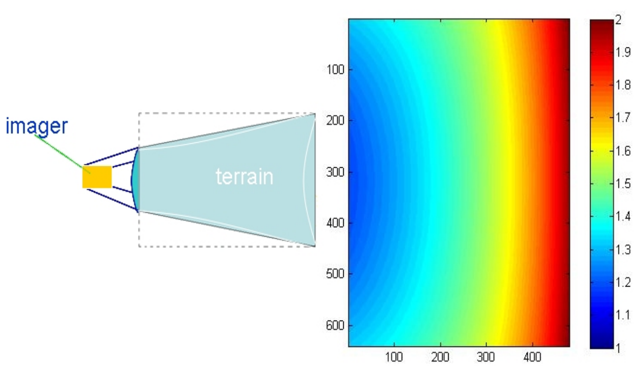

Figure 9. (Left) Flat Camera imaging system at angle to the surface [38]. (Right) Relative distance represented by each pixel.

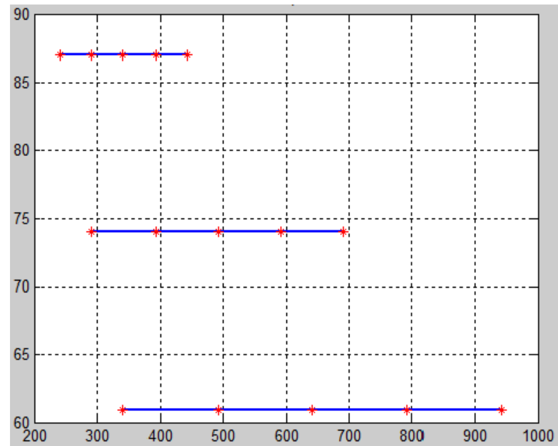

Figure 10. Percent overlap between successive frames as vehicle *speed* changes on a straight path at constant altitude (imager parallel to terrain) [38].

V. Summary and Conclusions

As discussed and highlighted in the previous sections, there is a critical need for highly reconfigurable and dynamic mission planning and rehearsal frameworks that are interoperable and support extensible sensor-workbench facilities. Such FOSS frameworks enable rapid deployment and efficient utilization of emerging disruptive sensor-net technologies. In particular, frameworks with sensor-packages that include camera modeling features, provide operationally realistic test beds that can be utilized for realistic MAV based image and sensor systems simulation and modeling development in support of tactical network-centric ISRT/IO Warfighter and First-Responder operations.

VI. Future Work

In addition to further exploring FOSS video and image processing resources, such as OSSIM and other FOSS image/video processing resources [47]-[48], semantic features of the MOVES Military Scenario Definition Language, (MSDL), Coalition Battle Management Language (CBM-L) and other recently developed capabilities [49]-[53] are also of particular interest for integration with a companion SenSOC effort called Enterprise Lexicon Services (ELS) [8]-[9]. Semantic capabilities, such as MSDL, CBM-L, and others identified within the context of ELS, are of great interest due to potential improvements in information interoperability that, in turn, enable provenance and pedigree capabilities [54] for EA/SOA based sensor-nets and related services. Finally, a long-term goal includes incorporating multi-objective optimization tools [55] into interoperable sensor-net frameworks for best matching mission needs and resourcing constraints with sensor-packages, platform features, and the growing wealth of FOSS and commercial COTS/GOTS sensor-net related technologies.

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